Fabrication of 20 nm patterns for automatic measurement of electron beam size using BEAMETR technique

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ABSTRACT

BEAMETR technique is developed for robust operator independent measurement of electron beam sizes in two coordinates. This method involves software and a specially designed pattern-sample. In this paper, we report the fabrication of this sample and the demonstration of beam size and shape measurements for different Scanning Electron Microscopes and operating conditions (voltage, aperture, astigmatism) with a good consistency. Electron Beam Lithography system (100 keV) was used for patterning; proximity correction was applied to improve pattern quality. In this chip version, the minimum feature linewidth was 20 nm after lift-off.

1. Introduction

Monitoring and tuning the beam size is critical for any electron beam system. The performance of defect inspection systems, Electron Beam Lithography (EBL) writers and Scanning Electron Microscopes (SEMs) depends greatly on their probe size and shape. The knife-edge method [1] usually used for electron beam size measurement is time consuming; the results are operator dependent and inaccurate. The resolution of the edge approach is mainly limited by the imperfect vertical profile of real edges and additional spikes in signals due to scattering of secondary electrons at the edges. Alternative techniques based on Fourier transform analysis have been proposed but are limited by measuring beam size equal to or larger than the minimum feature size of a fabricated pattern [2,3], or are complex when using combination of SEM and Transmission Electron Microscopy at equal beam voltage [4].

Most promising, recent works reported a method based on the spatial spectral analysis and comparison of a known pre-defined pattern to its image acquired by SEM [5,6]. The approach described in Ref. [5] is fast and allows reaching a high resolution; however, it does not allow automatic extraction of beam size. In the previous work, we have presented the BEAMETR (BEAm METRology) technique for automatic beam size measurements in two coordinates (x,y) [6]. BEAMETR includes a test sample with a pre-fabricated pattern and analysis software. While working well for beam sizes in the range of 15–150 nm using typical SEM images, our previous version of BEAMETR required acquisition of image with up to 3000 pixels in each coordinate when measuring beam sizes in the range of 8 nm down to the minimum 4 nm [6].

In this article, we extended the metrology range of BEAMETR down to 2 nm while simultaneously reducing required number of pixels in the image and the minimum feature size of our pattern. The fabrication of the BEAMETR sample with 20 nm minimum feature size using Electron Beam Lithography (EBL) and metal lift-off is described. Electron beam size measurements for using a few Scanning Electron Microscopes and operating conditions (voltage, aperture and astigmatism) are presented, results of measurements are discussed.

2. Design and fabrication

The principle of BEAMETR technique is to image a well-know sample with a pre-determined pattern and to compare the power spectra for both actual and designed images for automatic extraction of beam size. The spectral analysis is realized by a specially developed software which is described in details in Ref. [6]. The design of a specific pattern consists of gratings with variable pitch in horizontal and vertical directions (see Fig. 1). Both gratings are perpendicular to extract beam size values in (x,y) coordinates. Two scales of grating sizes are included in the same chip to extend the metrology range to electron beams to larger sizes.

A metrology sample was fabricated using Electron Beam Lithography and conventional lift-off process of Cr/Au layers on silicon. A thin film of positive e-beam resist is directly written by EBL (Vistec VB 300) at an accelerating voltage of 100 kV and a beam current of 500 pA. Commercial poly(methyl methacrylate) PMMA resist is

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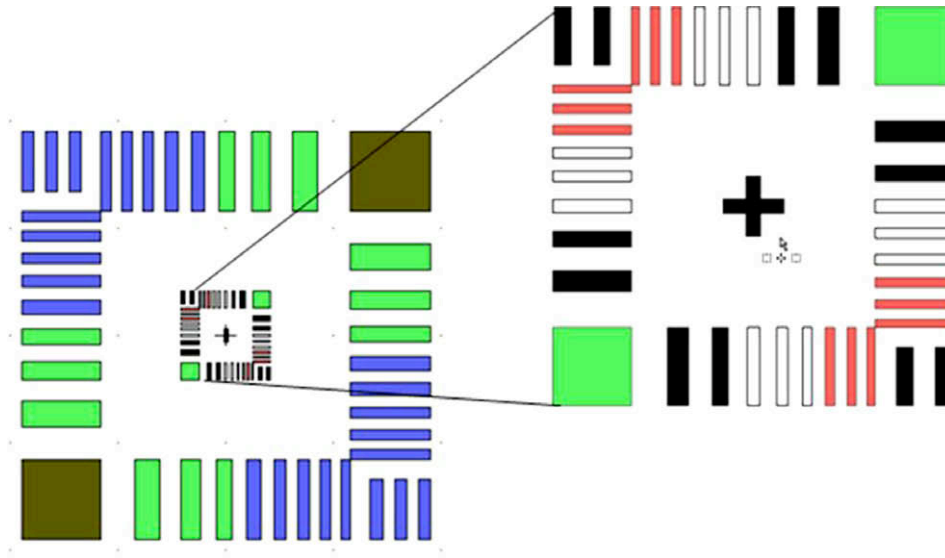E-mail address: cp@abeamtech.com (C. Peroz).

Fig. 1. BEAMETR pattern and its repartition into levels of electron beam exposure dose. Gratings are in horizontal and vertical directions with variable pitch size. Pattern is divided into six dose levels represented by color areas.

used to reach high resolution. PMMA resist (950 K) were spin-coated on silicon with thickness of 80 nm. Proximity correction was applied to improve patterning quality. Six levels of exposure dose were defined to solve the large size dispersion of our features (see Fig. 1). Preliminary dose matrix tests were performed to determine the right dose for each layer and their relative dose ratio. As general rule, the exposure dose increases for decreasing feature sizes. The exposure doses were varying between 1500 and 2500 $\mu C/cm^2$. Development of the patterned PMMA films was carried out in a solution of 7:3 isopropanol:water at -5 °C with ultra-sonication for 100 s. A cold development was used to increase the contrast and process latitude [7]. All samples then were cleaned by oxygen plasma for 10–20 s. Afterward, Cr (5 nm)/Au (15 nm) thin films were deposited using e-beam deposition (Semicore) followed by lift-off performed in dichloromethane bath. Fig. 2 depicts an example of the fabricated test-pattern including a large grating surrounding the test-pattern with the minimum line of 20 nm wide at the central grating.

3. Measurements and results

Beam measurement procedure consists of taking an image of the fabricated pattern using an e-beam and to load the image into BEAMETR software. The software analyzes the image and automatically extracts the beam size. The mathematical method is based on a spatial frequency analysis and comparison between power spectrum of the test-pattern and its SEM picture to extract the beam. A special attention is given to removal of image distortions and mis-alignment, and to noise reduction. More details are given in our previous work in Ref. [6]. The software involves automatic recognition of useful area for spectral analysis, fine alignment correction (rotation/off-set/distortions) of SEM images, noise reduction, and calibration of image magnification. Gaussian model is used as an assumption for beam shape in both (x,y) axis; the beam size can be different in x and y. SEM pictures are 8-bits and the number of pixels is not limited; smaller number of pixels (for example 512 or less) will result in smaller possible resolved beam size. Robustness of the BEAMETR software has been demonstrated earlier, when images of BEAMETR pattern were artificially blurred using known filters; the BEAMETR software loaded these images and determined beam sizes [6]. Three field emission SEM systems

from *Carl Zeiss SMT-AG* (Ultra 55, Ultra 60, XB1540) were characterized.

Fig. 3 displays a screenshot of BEAMETR software with measurement results of the analysis of BEAMETR 20 nm pattern. In these specific SEM settings at accelerating voltage $V_{acc} = 10$ kV and aperture size $\varnothing_{apr} = 30$ μm, the beam was found to be astigmatic with Full Width at Half Maximum (FWHM) values for beam diameter $\varnothing_{beam}$ of 3.2 and 2.3 nm in horizontal and vertical directions. One of the main advantages of BEAMETR technique is the
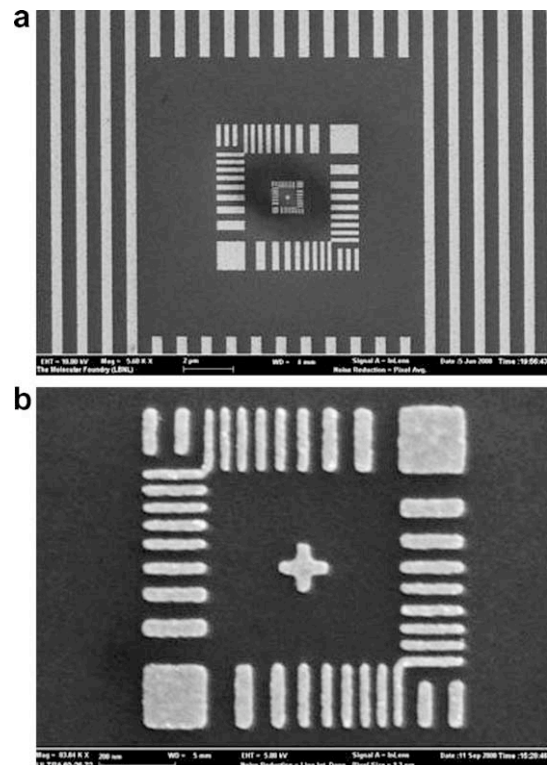

Fig. 2. SEM images of BEAMETR test-pattern (a) and its central pattern (b) with a minimum linewidth and pitch of 20 and 40 nm, respectively.
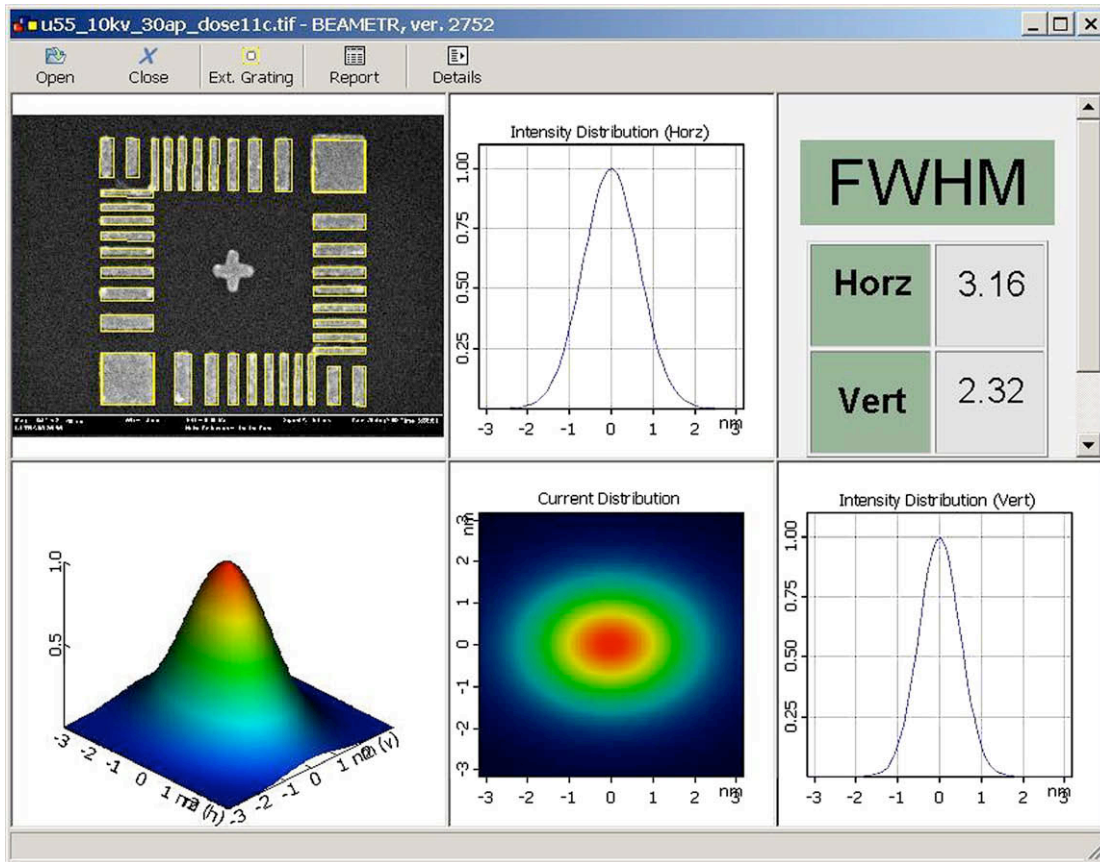
Fig. 3. Screenshot of BEAMETR software showing results of image analysis; the fabricated BEAMTER 20 nm pattern was used. SEM picture has been taken at V_{acc} = 10 kV and aperture size $\varnothing_{apr}$ = 30 μm using SEM *Zeiss* Ultra 55. The beam diameter was extracted to be 3.2 nm in horizontal direction and 2.3 nm in vertical direction.
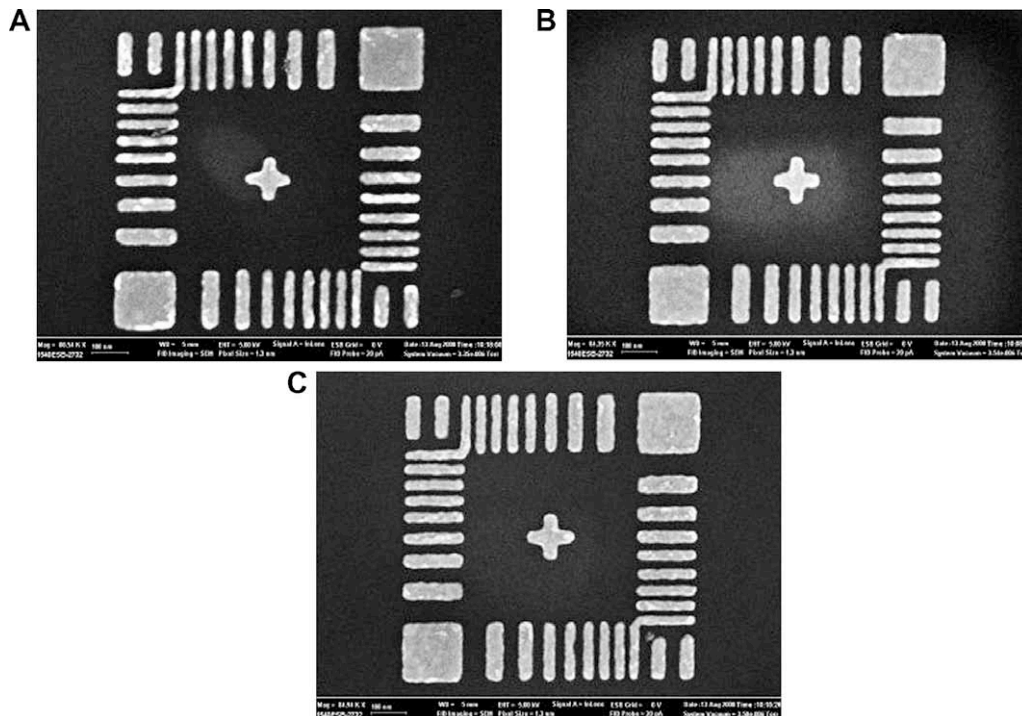

Fig. 4. SEM pictures of BEAMETR pattern for different exposure dose D_{max} giving different linewidth values at constant pitch (minimum = 40 nm) of gratings: (a) 22 nm (D_{max} = 2036 μC/cm^2), (b) 24 nm (D_{max} = 2357 μC/cm^2) and (c) 25 nm (D_{max} = 2475 μC/cm^2). SEM *Zeiss XB 1540* was used at V_{acc} = 5 kV and $\varnothing_{apr}$ = 30 μm.
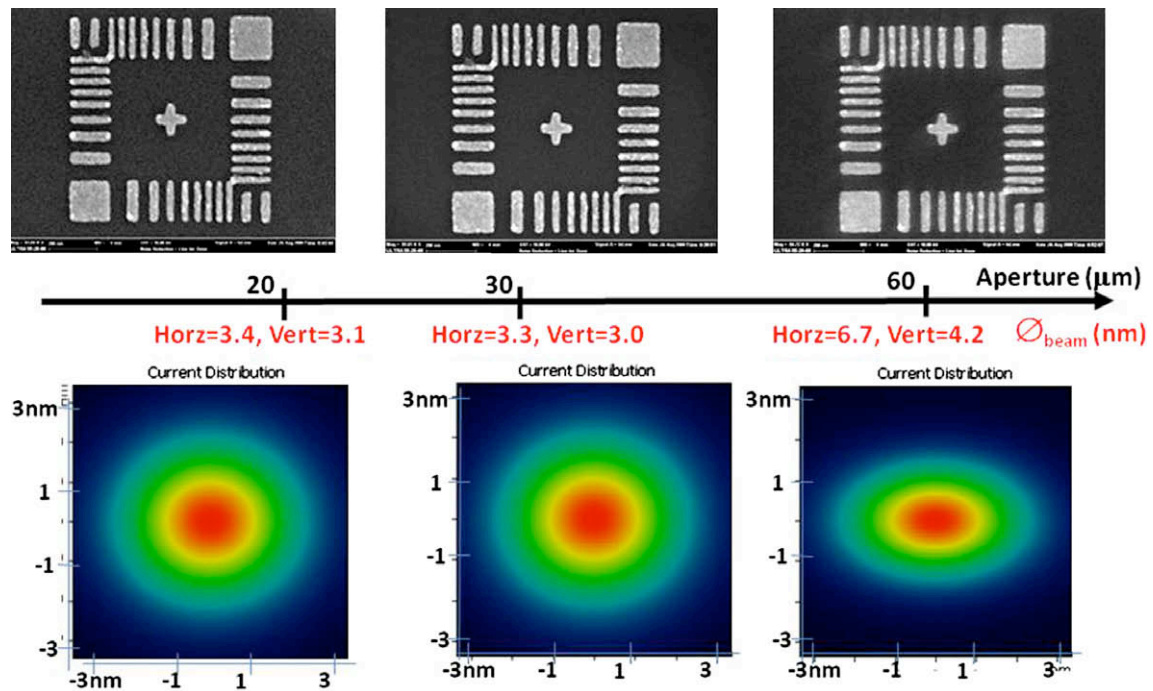
Fig. 5. SEM pictures of test-patterns and corresponding e-beam sizes extracted by BEAMETR technique at different apertures with sizes $\varnothing_{apr}$ = 20, 30 and 60 μm corresponding to averaged e-beam diameter in (x,y) axis $\varnothing_{beam}$ = (3.4 and 3.1 nm), (3.3 and 3.1 nm) and (6.7 and 4.2 nm). SEM *Zeiss* Ultra 55 was used.

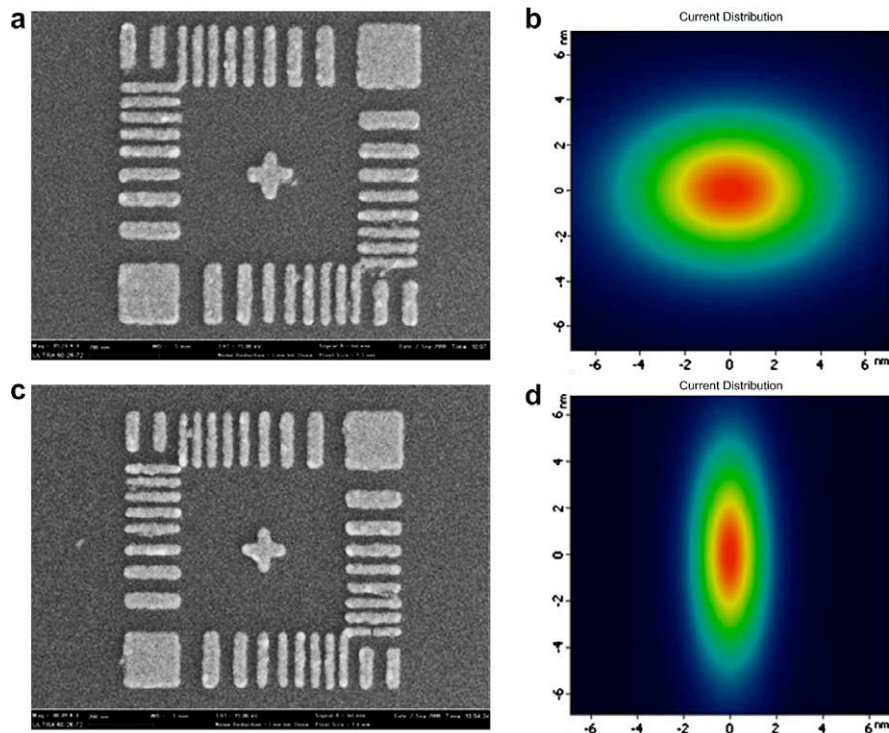**Fig. 6.** SEM pictures of BEAMETR pattern imaged at V_{acc} = 15 kV and aperture size $\varnothing_{apr}$ = 20 μm (*Zeiss* Ultra 60) and corresponding e-beam sizes when stigmatization was manually changed in one (Fig. 5a and b) and opposite (Fig. 5c and d) directions. The FWHM of e-beam in (x,y) axis are (7.1 and 5.9 nm) and (2.4 and 6.9 nm) for Fig. 5b and d.

consistency of these measurements; it is contrary to a high degree of operator dependence when using the knife-edge method. As an example, electron beam size has been measured on one same chip at same SEM conditions (scan rate, V_{acc} and $\varnothing_{apr}$), same working distance, and in the same measurements session (within 1 h) but for three different operating history: between three SEM images

of one chip, the operator moves sample, changes SEM conditions, contrast, and focusing; then comes back to the best condition. This procedure is tested for SEMs Ultra 55 and 60. The dispersion of $\varnothing_{beam}$ values was chronologically measured; it was within 50% when using edge technique and it was much closer when using BEAMETR: (3.1, 3.1 and 3.4 nm) and (2.7, 3.0 and 2.8 nm) for Ultra 55 and 60, respectively. This shows the good self-consistency of BEAMETR technique. Another advantage of BEAMETR method is its relative independence to the linewidth values of gratings which are quantitatively difficult to control at nanometer scale. We compared the $\varnothing_{beam}$ values extracted from three BEAMETR patterns fabricated with different exposure doses and thus three different linewidths but same pitch (see Fig. 4). The e-beam doses are tuned to D_{max} = 2036, 2357 and 2475 $\mu C/cm^2$ corresponding to linewidth of 22, 24 and 25 nm. The simulation results give $\varnothing_{beam}$ values of 3.4, 3.2 and 3.4 nm, respectively. These results confirm the high consistency of this approach and its relative independence on operators and gives reasonable process latitude for nanofabrication of BEAMETR chips.

A change of electron beam size and shape has been also observed when varying the beam voltage V_{acc} and aperture $\varnothing_{apr}$ of the SEM tools. The e-beam was manually focused before taking image. As illustration of our results, Fig. 5 shows SEM pictures of test-pattern and their e-beam size for aperture sizes $\varnothing_{apr}$ = 20, 30 and 60 μm at a fixed acceleration voltage of 10 kV. In this specific case, the average beam size remained quasi-constant around 3.2 nm for small aperture values and increased noticeably up to 5.5 nm when the aperture was changed from 30 to 60 μm. These results should be considered as qualitative to show some trends and it has to be noticed that the focusing of electron beam was more difficult for an aperture of 60 μm. In the same way, the size of the probe was larger when V_{acc} was decreased at constant aperture. Imaging with SEM Ultra 60 of a BEAMETR 20 nm pattern found variations of beam sizes $\varnothing_{beam}$ = 4.3, 4.2, 2.7 and 3.0 nm for V_{acc} = 2, 5, 10 and 15 kV, respectively, at the aperture size $\varnothing_{apr}$ = 20 μm. These results are consistent with expected behavior of electron beams: the beam gets smaller at higher acceleration voltage or at the smaller aperture. Fig. 6 illustrates the effect of significant defocusing the e-beam in horizontal (Fig. 6a and b) and vertical axis (Fig. 6c and d) when stigmatization was manually changed at constant V_{acc} and $\varnothing_{apr}$ values.

Comparative analysis of measurements for our three SEM tools revealed that the characteristics of these SEMs are similar with an e-beam size around 2.5–3.5 nm at V_{acc} = 10 kV and $\varnothing_{apr}$ = 30 μm. Note that all these measurements represent beam size at specific setting and environment of an SEM, operator qualification etc., it is not the ultimate smallest beam size of a specific SEM type. The advantage of BEAMETR is that it can be easily used to measure beam size at any desired moment. This is especially important for CD-SEMs, where results greatly depend on beam size.

4. Conclusion

BEAMETR technique was demonstrated as an attractive solution for electron beam metrology. The association of a specially designed and fabricated pattern and software offer an easy and fast way to measure e-beam size. A powerful spectral analysis of variable pitch gratings as small than 20/40 nm minimum linewidth/pitch allows measuring probe sizes down to 2.3 nm with a good consistency and reproducibility. A set of measurements using different SEMs and under various imaging conditions was taken; these examples demonstrated the usability of the BEAMETR for metrology of electron beam systems.

Acknowledgements

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